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THERMODYNAMIC EFFECTS OF
CAVITATION OF AN 80.6° HELICAL
INDUCER OPERATED IN HYDROGEN

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Cleveland, Ohio



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SUMMARY

An 80.6° helical inducer was used to evaluate the thermodynamic effects of cavitation in liquid hydrogen over a range of liquid temperatures and flow coefficients at two rotative speeds. The liquid temperatures ranged from 31.0° to 40.0° R (17.2 to 22.2 K). These tests were conducted at rotative speeds of 25 000 and 30 000 rpm over a range of flow coefficients from 0.093 to 0.118. Although the magnitude of the predicted thermodynamic effects of cavitation was less for 25 000 rpm than that for 30 000 rpm, the trends were the same with liquid temperature and flow coefficient. The thermodynamic effects increased with increasing liquid temperature and decreased with increasing flow coefficient. The experimental values of required net positive suction head were in good agreement with those obtained using a semiempirical prediction method.

INTRODUCTION

The performance of a cavitating inducer in a cryogenic liquid-propellant rocket engine is dependent on the physical properties of the pumped fluid, the flow conditions, and the heat-transfer effects between the liquid and vapor cavity. These combined effects, which are termed the thermodynamic effects of cavitation, are discussed in detail in reference 1. For an inducer operated in liquid hydrogen, these thermodynamic effects give a marked improvement in the cavitation performance over that obtained with room-temperature water. The cavitation performance obtained with several inducers operated in liquid hydrogen over a range of temperatures is presented in references 2 to 8.

A method for predicting the thermodynamic effects of cavitation and thus the cavitation performance of inducers is presented in reference 8. The prediction method is based on results obtained from Venturi cavitation studies using several different liquids (refs. 1 and 9 to 11). This method has been used to predict the cavitation performance

of several inducers and pumps handling various liquids over a range of liquid temperatures and rotative speeds (refs. 3, 4, and 8).

The objective of this investigation was to evaluate the thermodynamic effects of cavitation in liquid hydrogen for an 80.6° helical inducer. The experimental values of required net positive suction head NPSH for a cavitating-to-noncavitating head-rise-coefficient ratio of 0.70 were used in conjunction with the method of reference 8 to predict the thermodynamic effects of cavitation. Predicted values of required NPSH were compared with those determined experimentally. The NPSH requirements for the inducer were determined in each of three different inlet line configurations. The experimental inducer was tested over a liquid temperature range of 31.0° to 40.0° R (17.2 to 22.2 K), for flow coefficients from 0.093 to 0.118, and for rotative speeds of 25 000 and 30 000 rpm. This investigation was conducted at the Plum Brook Station of the NASA Lewis Research Center.

APPARATUS AND PROCEDURE

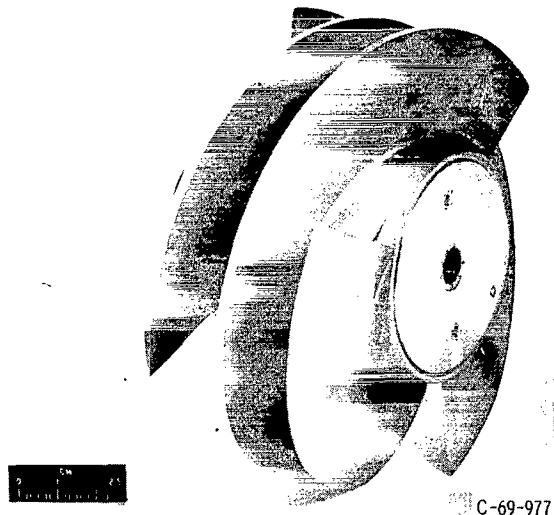
Test Rotor

The experimental rotor used in this investigation was a three-bladed helical inducer with a tip helix angle of 80.6° . The flat-plate helical inducer has a constant tip diameter of 4.980 inches (12.649 cm) and a constant hub- to tip-radius ratio of 0.5. A photograph and significant design features of the 80.6° helical inducer are presented in figure 1. The leading edge of the inducer was faired on the suction surface only (see fig. 1). This rotor was tested in the liquid-hydrogen facility described in references 2 and 4.

The inducer was tested in three inlet line configurations. One inlet line was a short shroud configuration that simulated an inducer closely coupled to the tank (ref. 5). The other configurations were a long inlet line with and without a stationary centerbody (refs. 6 and 7).

Test Procedure

The data used for this evaluation of the thermodynamic effects of cavitation are from references 5 to 7. For those tests, the net positive suction head NPSH, measured at the inducer inlet, was slowly decreased from a value that corresponded to noncavitating conditions. The NPSH was decreased until the head rise deteriorated because of cavitation. During each test, the flow rate, liquid temperature, and rotative speed were maintained essentially constant.



Tip helix angle (from axial direction), deg	80.6
Rotor tip diameter, in. (cm)	4.980 (12.649)
Rotor hub diameter, in. (cm)	2.478 (6.294)
Hub-tip ratio	0.496
Number of blades	3
Axial length, in. (cm)	2.00 (5.08)
Peripheral extent of blades, deg	280
Tip chord length, in. (cm)	12.35 (31.37)
Hub chord length, in. (cm)	6.36 (16.15)
Solidity at tip	2.350
Tip blade thickness, in. (cm)	0.100 (0.254)
Hub blade thickness, in. (cm)	0.150 (0.381)
Calculated radial tip clearance at hydrogen temperature, in. (cm)	0.025 (0.064)
Ratio of tip clearance to blade height	0.020
Material	6061-T6 Aluminum

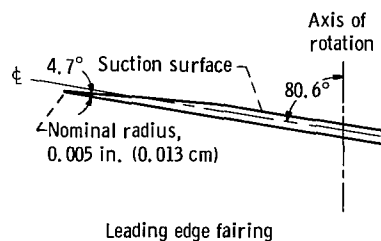
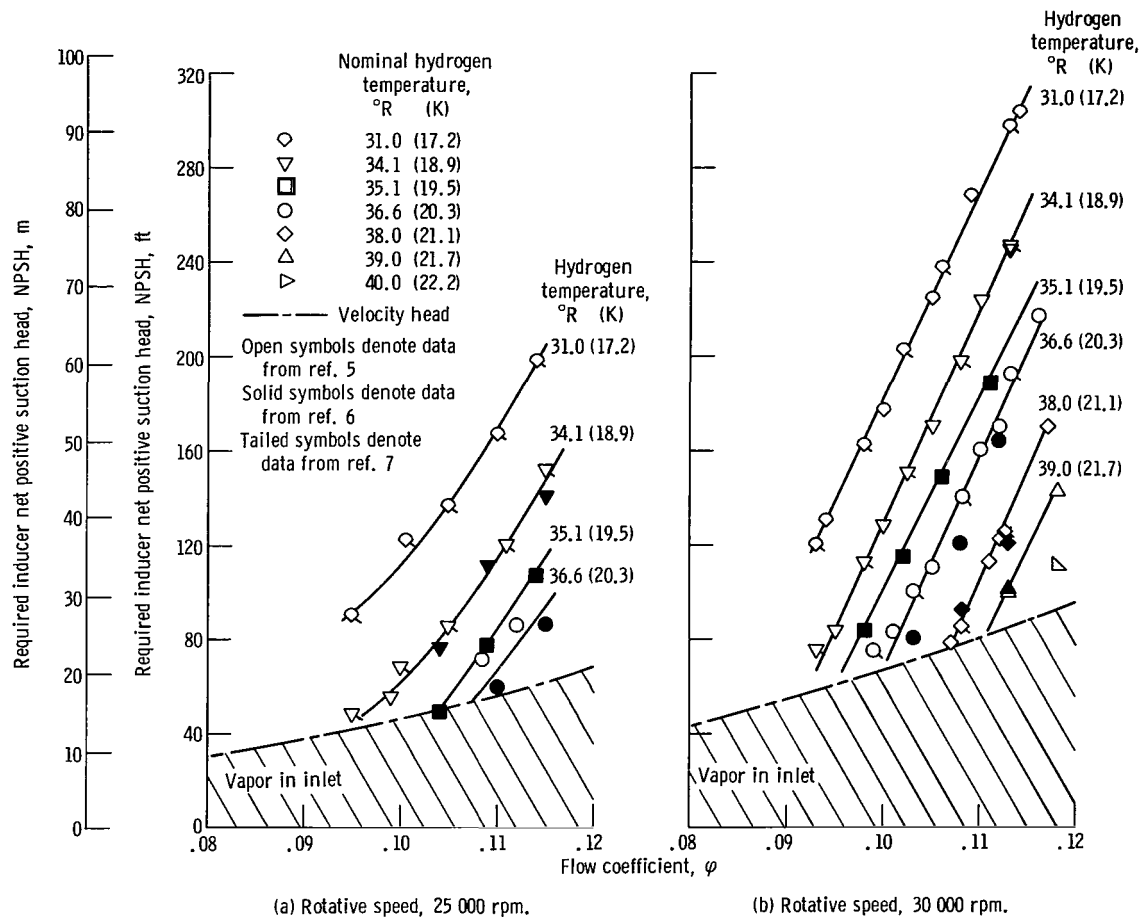


Figure 1. - Geometric details of 80.6° helical inducer.



RESULTS AND DISCUSSION

Cavitation Performance

The cavitation performance for the 80.6 $^{\circ}$ helical inducer operated in liquid hydrogen is presented in references 5 to 7. The inducer was tested over a range of liquid temperatures and flow coefficients at two rotative speeds. The inducer NPSH requirements were measured for each of three different inlet line configurations. A summary of the results obtained is presented in figure 2. In this figure, the required NPSH for a head-rise-coefficient ratio ψ/ψ_{NC} of 0.70 is plotted as a function of flow coefficient for several nominal hydrogen temperatures and for rotative speeds of 25 000 and 30 000 rpm (figs. 2(a) and (b), respectively).

Although the magnitude of the required NPSH is greater for the higher rotative speed, the trends observed with varying liquid temperature and flow coefficient are the

same for both rotative speeds. At a constant flow coefficient, the required NPSH decreases with increasing liquid temperature. For a constant liquid temperature, the required NPSH increases with increasing flow coefficient. The required NPSH for a constant liquid temperature and flow coefficient is approximately the same for the inducer with each of the three inlet line configurations (fig. 2(b)).

The dashed lines in figure 2 represent values of NPSH that are equal to the fluid velocity head at the inducer inlet. For this condition, the local static pressure at the inducer inlet is equal to the fluid vapor pressure. At lower values of NPSH (shaded area of fig. 2), the fluid will boil, and the vapor is ingested by the inducer. With this two-phase flow, the through-flow velocity will increase, and the effective flow coefficient will be higher (ref. 12). Because of this change in flow coefficient, data taken at values of NPSH less than the inlet velocity head are not used herein.

Thermodynamic Effects of Cavitation

A method for predicting the thermodynamic effects of cavitation and the cavitation performance of inducers is presented in detail in reference 8. A brief summary of this method is presented herein. A heat balance between the heat required for vaporization and that drawn from the liquid adjacent to the cavity is used to show that the cavity pressure depression below free-stream vapor pressure is

$$\Delta h_v = \left(\frac{\rho_v}{\rho_l} \right) \left(\frac{L}{C_l} \right) \left(\frac{dh_v}{dT} \right) \left(\frac{\gamma_v}{\gamma_l} \right) \quad (1)$$

With known properties of hydrogen, values of vapor- to liquid-volume ratio γ_v/γ_l as a function of Δh_v can be obtained by numerical integration of equation (1). This integration takes into account changes in properties as the equilibrium temperature drops as a result of the evaporative cooling. The calculated depression in vapor pressure Δh_v is plotted as a function of vapor- to liquid-volume ratio γ_v/γ_l for a range of liquid-hydrogen temperatures in figure 3. Equation (1) cannot be used directly to predict the required NPSH because the absolute value of γ_v/γ_l is not known. However, it was shown that, if a reference value of γ_v/γ_l is established experimentally by determining Δh_v , values of γ_v/γ_l relative to this reference value can be estimated from the following equation:

$$\frac{\gamma_v}{\gamma_l} = \left(\frac{\gamma_v}{\gamma_l} \right)_{\text{ref}} \left(\frac{\alpha_{\text{ref}}}{\alpha} \right) \left(\frac{N}{N_{\text{ref}}} \right)^{0.8} \quad (2)$$

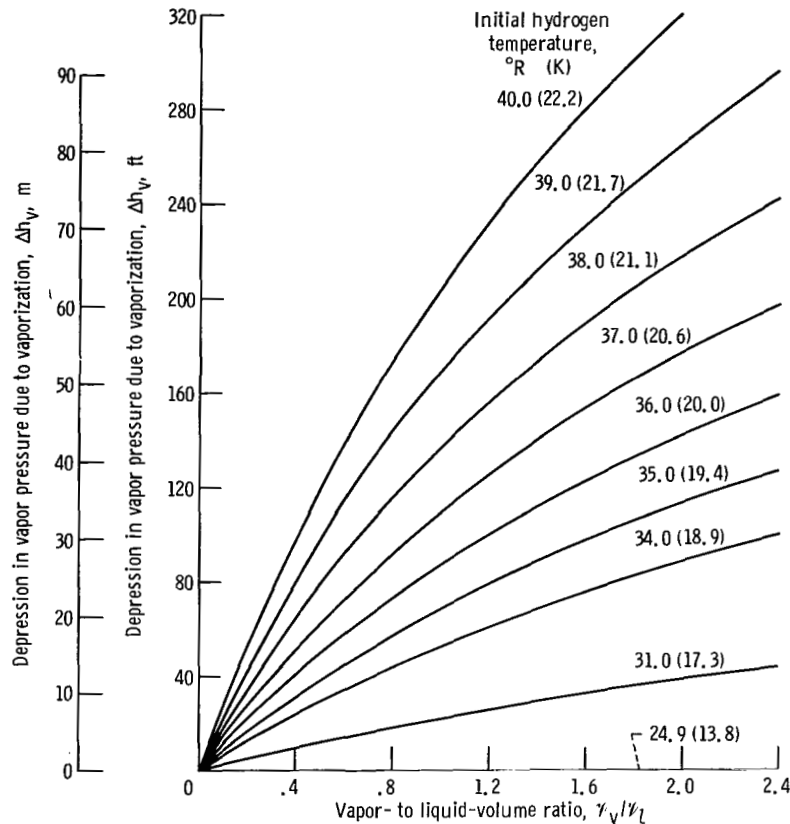


Figure 3. - Calculated vapor pressure depression due to vaporization as function of volume ratio for several liquid-hydrogen temperatures.

The foregoing equation assumes geometrically similar cavitating flow conditions (i. e., the same flow coefficient and the same head-rise-coefficient ratio for the predicted condition as those for the reference condition).

The inducer cavitation performance for a constant flow coefficient and head-rise-coefficient ratio is predicted with the following equation (ref. 8):

$$\frac{\text{NPSH} + \Delta h_v}{\text{NPSH}_{\text{ref}} + (\Delta h_v)_{\text{ref}}} = \left(\frac{N}{N_{\text{ref}}} \right)^2 \quad (3)$$

This relation requires that two experimental test points be available for the inducer of interest. These experimental data can be for any combination of liquid, liquid temperature, or rotative speed provided that at least one set of data exhibits a measurable thermodynamic effect. From these experimental data, the cavitation performance for the inducer can be predicted for any liquid, liquid temperature, or rotative speed. For

the present study, changes in liquid temperature and rotative speed at specified flow coefficients were considered.

The faired NPSH values at nominal liquid temperatures of 31.0° and 34.1° R (17.2 and 18.9 K) at a rotative speed of $30\,000$ rpm (fig. 2(b)) were arbitrarily chosen as the two reference curves to predict the magnitude of the thermodynamic effects of cavitation. These required NPSH values were used in equation (3) to obtain a value of $\Delta h_{v, \text{ref}} - \Delta h_v$ at a given flow coefficient. An assumed value of $\Delta h_{v, \text{ref}}$ was used in an iterative process with figure 3 (eq. (1)) and equation (2) to solve for the values of $\Delta h_{v, \text{ref}}$ and Δh_v that satisfy equation (3). The thermodynamic effects Δh_v at other temperatures and rotative speeds were then predicted by using equation (2) and the reference value of γ_v/γ_l obtained from the determined value of $\Delta h_{v, \text{ref}}$. This procedure was used over the range of flow coefficients.

The predicted magnitude of the thermodynamic effects of cavitation is given in figures 4(a) and (b) for rotative speeds of $25\,000$ and $30\,000$ rpm, respectively. The values

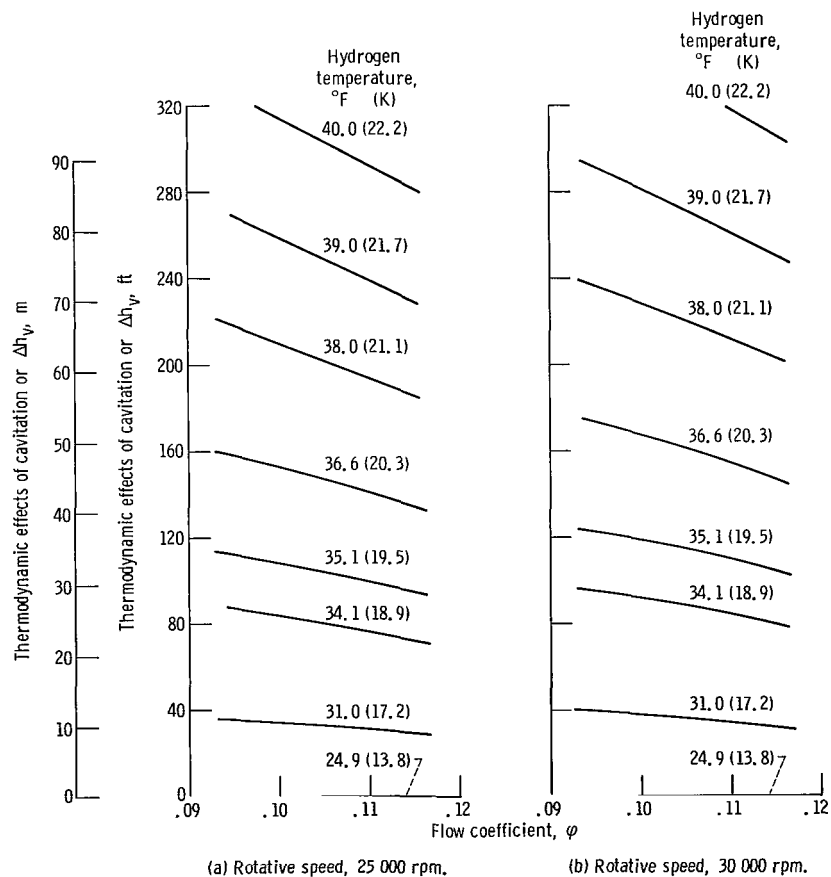


Figure 4. - Predicted thermodynamic effects of cavitation as function of flow coefficient for several hydrogen temperatures for 80.6° helical inducer. Head-rise-coefficient ratio, 0.70.

of Δh_v increase with increasing liquid temperature and decrease with increasing flow coefficient. For the same liquid temperature and flow coefficient, the value of Δh_v for 30 000 rpm is greater than that for 25 000 rpm. At a rotative speed of 30 000 rpm and a flow coefficient of 0.105, the predicted values of Δh_v increased from 36 feet (11 m) at a liquid temperature of 31.0° R (17.2 K) to 272 feet (83 m) at a temperature of 39.0° R (21.7 K). At a liquid temperature of 36.6° R (20.3 K) and rotative speed of 30 000 rpm, Δh_v decreased almost linearly from 174 to 148 feet (53 to 45 m) as the flow coefficient was increased from 0.095 to 0.115, whereas, for a rotative speed of 25 000 rpm, the decrease was from 148 to 134 feet (45 to 41 m) for the same increase in flow coefficient.

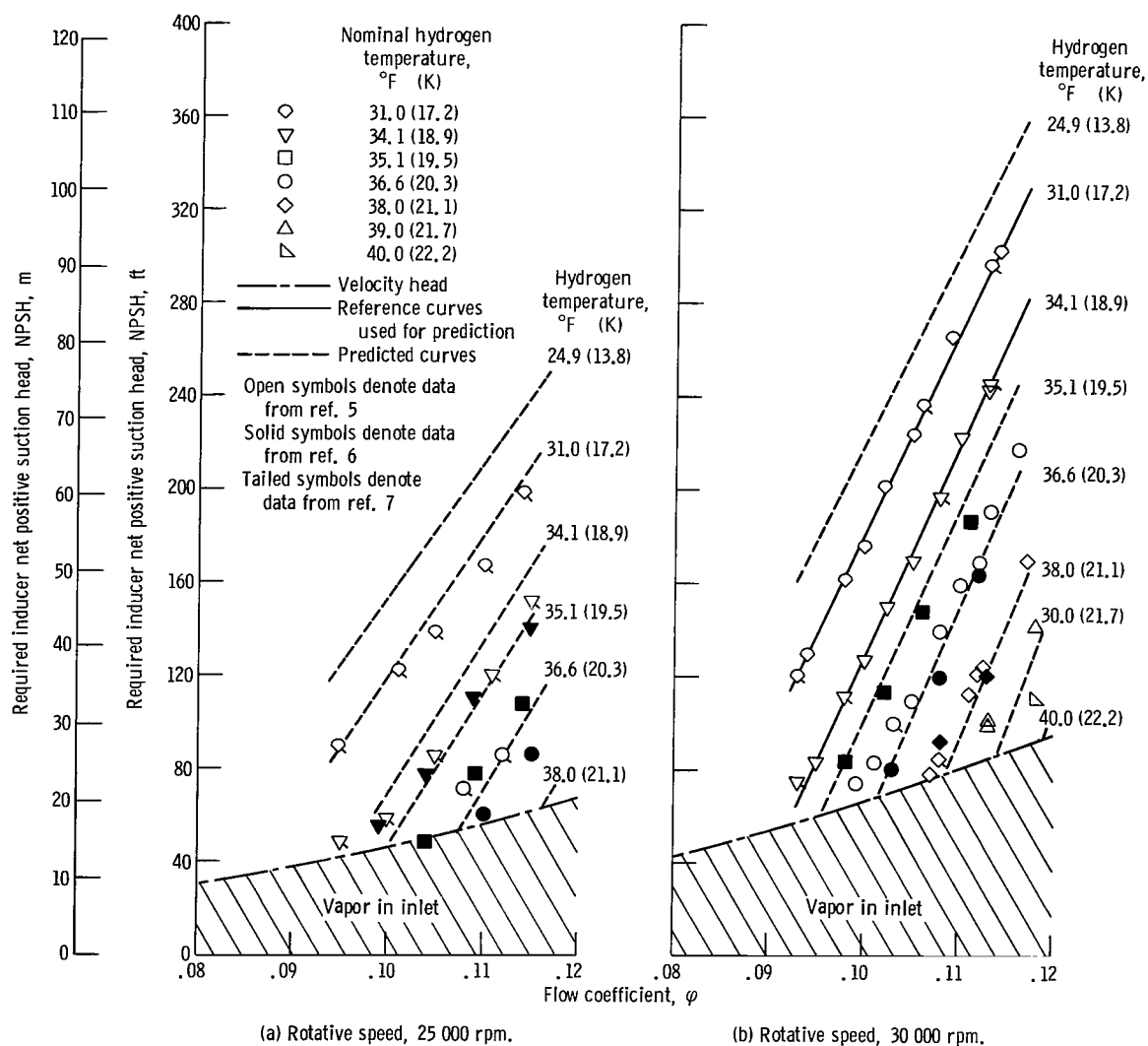


Figure 5. - Comparison of predicted and measured net positive suction head for 80.6° helical inducer in hydrogen. Head-rise-coefficient ratio, 0.70.

Comparison of Predicted and Measured Net Positive Suction Head

A comparison between the predicted and experimental values of required inducer NPSH at a head-rise-coefficient ratio of 0.70 is shown in figure 5. The data points are repeated from figure 2. The reference data (solid lines) at 31.0° and 34.1° R (17.2 and 18.9 K) for a rotative speed of 30 000 rpm were used to predict the required NPSH at other temperatures and at 25 000 rpm. The predicted curves are shown as dashed lines.

For a rotative speed of 30 000 rpm (fig. 5(b)), good agreement is shown between the predicted and measured NPSH. For a rotative speed of 25 000 rpm (fig. 5(a)), the predicted values are slightly greater than the measured values. The predicted required NPSH for triple-point (24.9° R or 13.8 K) hydrogen is also shown in figure 5. At the triple point, the thermodynamic effects of cavitation are zero; thus, the cavitation performance should be the same as that for cold water.

SUMMARY OF RESULTS

An 80.6° helical inducer was investigated with three different inlet line configurations, and the net positive suction head NPSH requirements were experimentally determined at the inducer inlet for each configuration. The required NPSH for a cavitating-to-noncavitating head-rise-coefficient ratio of 0.70 was used in conjunction with a semiempirical method to predict the magnitude of the thermodynamic effects of cavitation. The predicted and measured values of required NPSH were compared. The experimental inducer was tested in hydrogen over a range of liquid temperatures from 31.0° to 40.0° R (17.2 to 22.2 K). The flow coefficient was varied from 0.093 to 0.118 at rotative speeds of 25 000 and 30 000 rpm. The investigation yielded the following results:

1. At a rotative speed of 30 000 rpm and a flow coefficient of 0.105, the predicted thermodynamic effects of cavitation increased from 36 feet (11 m) at a liquid temperature of 31.0° R (17.2 K) to 272 feet (83 m) at a temperature of 39.0° R (21.7 K).

2. At a rotative speed of 30 000 rpm and a liquid temperature of 36.6° R (20.3 K), the thermodynamic effects of cavitation decreased almost linearly from 174 to 148 feet (53 to 45 m) as the flow coefficient was increased from 0.095 to 0.115.

3. The magnitude of the thermodynamic effects of cavitation was less for a rotative speed of 25 000 rpm than that for a rotative speed of 30 000 rpm. The trends with increasing liquid temperature and flow coefficient were the same for both rotative speeds.

4. Good agreement was obtained between predicted and measured values of required NPSH.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 28, 1969,
128-31.

APPENDIX - SYMBOLS

C_l	specific heat of liquid, Btu/(lbm)(°R); J/(kg)(K)	\mathcal{V}_l	volume of liquid involved in cav- itation process, in. ³ ; cm ³
dh_v/dT	slope of vapor pressure head to temperature curve, ft/°R; m/K	\mathcal{V}_v	volume of vapor, in. ³ ; cm ³
g	acceleration due to gravity, ft/sec ² ; m/sec ²	α	thermal diffusivity of liquid, $k/\rho_l C_l$, ft ² /hr; m ² /hr
ΔH	pump head rise based on inlet density, ft of liquid; m of liquid	ρ_l	density of liquid, lbm/ft ³ ; kg/m ³
Δh_v	decrease in vapor pressure because of vaporization (magnitude of thermody- namic effect of cavitation), ft of liquid; m of liquid	ρ_v	density of vapor, lbm/ft ³ ; kg/m ³
k	liquid thermal conductivity, Btu/(hr)(ft)(°R); J/(hr)(m)(K)	ϕ	flow coefficient, V_a/U_t
L	latent heat of vaporization, Btu/lbm; J/kg	ψ	head-rise coefficient, $g \Delta H/U_t^2$
N	rotative speed, rpm	ψ/ψ_{NC}	cavitating-to-noncavitating head- rise-coefficient ratio
$NPSH$	net positive suction head, ft of liquid; m of liquid	Subscripts:	
U_t	blade tip speed, ft/sec; m/sec	NC	noncavitating
V_a	average axial velocity at in- ducer inlet, ft/sec; m/sec	ref	reference value obtained from ex- perimental tests

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